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Voltage Distortion at the 480 VAC Bus Feeding PowerPlus Units

For bus voltages 69 kV and below, Table 11.1 of IEEE 519-1992 calls for a total voltage distortion of 5.0% maximum with individual harmonic distortion not to exceed 3.0%.

Since power converters are a nonlinear load to the power system, this means that they generate harmonics other than the fundamental 60 Hz. The PowerPlus units use an off-line front-end that consists of a three phase full wave diode rectifier and an L-C filter. This means that the PowerPlus presents itself to the bus system as a harmonic current source generating harmonics of frequency order (6n ± 1) where n = 60 Hz. Each harmonic component is approximately of magnitude 1/(6n ± 1) for an ideal system with no source impedance.

As these current harmonics circulate back into the utility system, a voltage $\mathbf{V_n = I_n{*}Z_n}$ is developed across the impedance looking back into the system (Z_n) for each harmonic component. Because of the harmonic voltages developed across the bus impedance, the sinusoidal bus voltage becomes distorted. By designating the total harmonic voltage distortion as THD_V, the voltage distortion can be calculated as

$$\mathbf{THD_V = [(I_2{*}2)^2 + (I_3{*}3)^2 ++\ldots. ++ (I_n{*}n)^2]^{1/2}/I_{SC} * 100\%}$$

where

- **n** is the order of the current harmonic and ranges from 2 to infinity
- $\mathbf{I_n}$ is the magnitude of the nth order current harmonic
- $\mathbf{I_{SC}}$ is the short circuit current at the 480 Vac bus

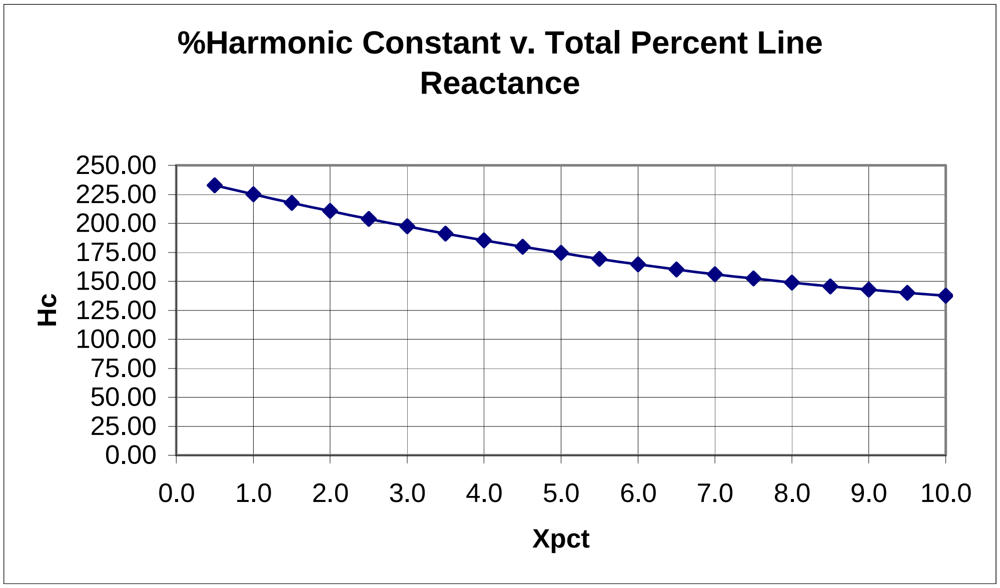
In *Power Electronic Converter Harmonics* by Derek Paice, this calculation is simplified by introducing Hc, the % harmonic constant. The above equation can now be expressed as

$$\mathbf{THD_V = Hc{*}I_{FL}/I_{SC}}$$

where

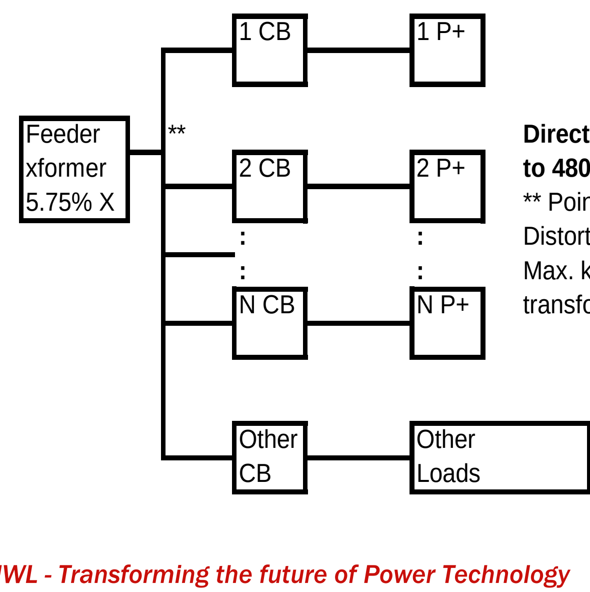
- **Hc** is the % harmonic constant
- $\mathbf{I_{FL}}$ is the full load fundamental current of the power converters (in this case the PowerPlus units)
- $\mathbf{I_{SC}}$ is the short circuit current at the 480 Vac bus

Paice has then tabulated the value for Hc for systems where the source has a pre-existing 2.5 % fifth order harmonic distortion and 1% negative sequence voltage components (to allow for some slight imbalance between phases). The result of all of this is that Hc represents more of a real world value. For a 3 phase full wave diode bridge feeding an L-C filter, his results are shown in the following graph.



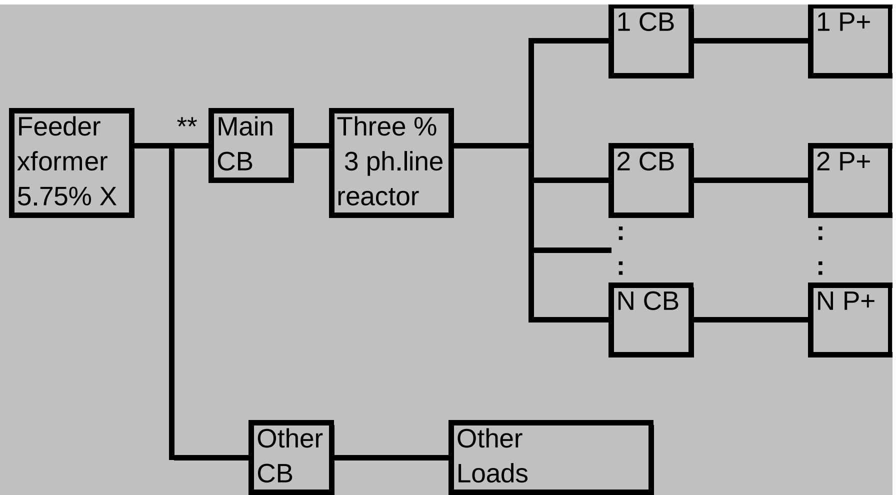
Please note that the horizontal scale in the above graph is for total percent reactance, which includes cable reactance and line reactors as well as the short circuit impedance of the 480 VAC feeder transformer. It is important to note that all of the preceding analysis is based on no power factor capacitors being on the feeder system. Once power factor capacitors are introduced, harmonic resonances can be setup and the analysis becomes more complex.

For starters, assume that the PowerPlus units connect right to the 480 VAC bus with negligible cable reactance and no external line reactors. Going through some mathematical manipulation, Paice has estimated that the kW load of the power converters (PowerPlus units in this case) has to be less than or equal to 40% of the transformer rating for the THD_V to be within the 5% limit of IEEE 519-1992. This analysis is based on the impedance of the bus feeder transformer typically being 5.75%.



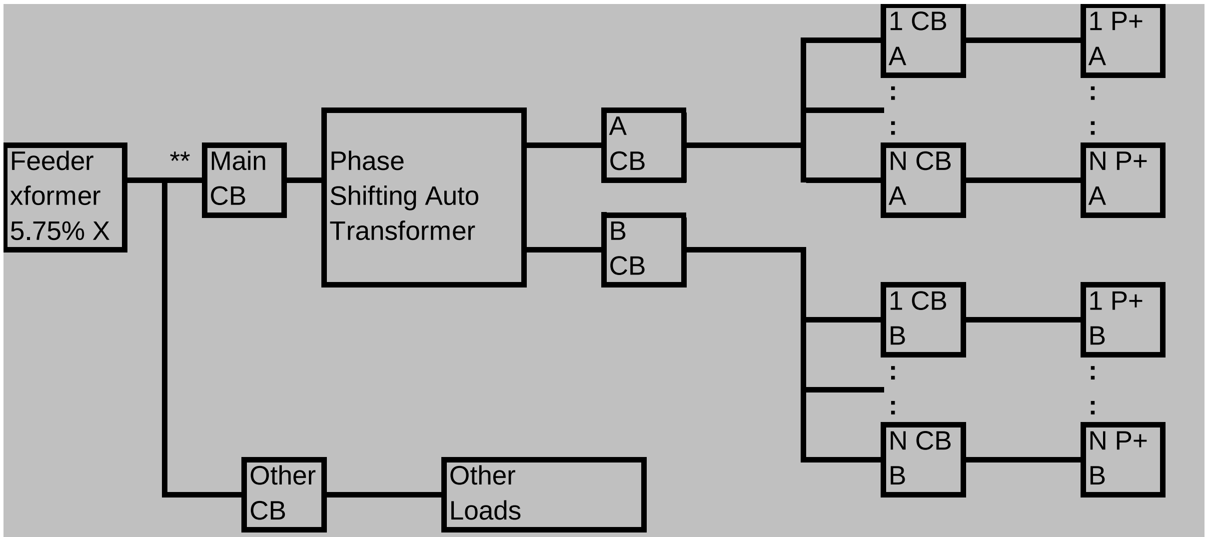
Direct Connection of PowerPlus Units (P+) to 480 Vac Bus feeding circuit breakers (CB)
** Point of Common Coupling at which Voltage Distortion is Measured.
Max. kW load for THDv = 5% is 40% of feeder transformer (xformer) rating

Inserting 3% line reactance (a three phase line reactor) between the feeder transformer and the 480 VAC bus feeding the PowerPlus units allows the kW load to be increased to 50% of the transformer rating while still maintaining the 5% THD_V level.



Insertion of 3% 3phase line reactor between 480 Vac Bus and circuit breakers feeding each PowerPlus unit (P+)
** Point of Common Coupling at which Voltage Distortion is Measured.
Max. kW load for THDv = 5% is 50% of feeder transformer (xformer) rating

Another cost effective means to increase the allowable kW level (as a percentage of feeder transformer rating) is to connect a phase-shifting autotransformer at the output of the feeder transformer and split the 480 VAC bus feeding the PowerPlus units into two equally loaded sections. This technique effectively produces a 12 pulse load to the feeder transformer and lowers Hc to 44% to 50% of the Hc value for a 6 pulse system. The result is that the PowerPlus load can now reach 80 to 90% of the feeder transformer rating while still maintaining a THD_V of 5.0%.



Insertion of phase shifting autotransformer to eliminate most of the 5th and 7th harmonics resulting in a large reduction of Hc. Half of the PowerPlus units (P+) are fed from one bus section (A) and half from the other bus section (B).
** Point of Common Coupling at which Voltage Distortion is Measured.
Max. kW load for THDv = 5% is 80% to 90% of feeder transformer (xformer) rating

One important aspect for consideration is factoring in the actual application. What is the typical kW loading for the PowerPlus units operating on an electrostatic precipitator? On a functioning precipitator, the PowerPlus units will never operate with all units at full rated kW output. The inlet fields will operate at an arc-over voltage that typically runs 8 to 10 kV below rated with currents less than 30% of rated. As units are placed closer to the outlet fields, the current will increase as the dust load decreases. At any given time, the output of all units will be approximately 50-60% of total rated load. Prior to planning the bus feeds to the PowerPlus units, it would be beneficial to review electrical data from the same or a similar ESP, and then allow some room for improvements possible with the PowerPlus units.

In addition to voltage distortion, there are two other harmonic issues to consider when connecting a nonlinear load to the power system: voltage notching and current harmonics. The current harmonics are particularly important since they relate to the feeder transformer rating.

For the case of the PowerPlus units, voltage notching is the result of the input diodes switching (commutating) from one phase to the next as the rectified DC waveform is created. Notches created in the voltage at the feeder bus will sometimes affect other equipment that may be sensitive to these notches (one example might be the synchronization circuits on SCR controllers). If this appears to be a problem, the use of a 3 phase line reactor as illustrated above will considerably reduce the notching. IEEE 519-1992 recommendations for voltage notching are as defined below.

Low Voltage System Classification and Distortion Limits

Parameter	Special Applications[2]	General system	Dedicated System[3]
Notch depth	10%	20%	50%
THD_V	3%	5%	10%
Notch Area[1] (A_N)	16400	22800	36500

1. Notch area is in Volt-microseconds units and is for a 480 V feed. For feeders of a different voltage, V, multiply the values in the table by V/480.
2. Special Applications include hospitals and airports.
3. A dedicated system is one where the feeder powers only the power supply load (such as all PowerPlus units).

As mentioned at the start of this paper, power converters generate current harmonics. In addition to distorting the bus voltage, these harmonics also circulate through the windings of the feeder transformer, creating additional heat. ANSI standard C57.110-1986, "IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Currents" addresses how to rate the transformer based on the harmonic content of the current waveform. In order to determine the transformer's ability to handle these nonsinusoidal loads, the harmonic profile of the current waveform needs to be calculated. The next step is to work with the transformer manufacturer so that the harmonic component values can be applied to the transformer design per ANSI C57.110-1986. The result of this analysis is that the transformer will then be rated for a new value (I_{max}) that is less the nameplate rated current.

Paice, in his book, addresses the case where the only load connected to the 480 VAC bus is the power converters. He defines the variable k to be

$$k = [1 + (Hc/100)^2]*(I_1/I_{RMS})^2$$

where

Hc is the % harmonic constant as defined above
I_1 is the fundamental current (60 Hz component)
I_{RMS} is the total rms current

The maximum allowable per unit transformer current can then be calculated using the following:

$$I_{max}\,(pu) = [(1 + P_{EC\text{-}R(pu)})/(1 + k*P_{EC\text{-}R(pu)})]^{1/2}$$

where

k is as defined above
$P_{EC\text{-}R(pu)}$ are the per unit eddy losses of the transformer windings under rated resistive load conditions. A typical value is 0.15.

For example, let us apply the solution using a phase-shifting autotransformer to this calculation. As stated, Hc for the 12 pulse solution is roughly ½ of the value for the 6 pulse system. Let the power converter load be 85% of the transformer rating. The effective impedance for this load is then .85*(5.75) = 4.89%. Using the graph for Hc for a 6 pulse system, we obtain Hc = 176. Hc for the 12 pulse system is then approximately 88. For the PowerPlus units, I_1/I_{RMS}, is roughly .95 at rated output. Solving for k, k = 1.60. Lastly, the maximum per unit current rating for the feeder transformer is I_{max} (pu) = .96. For this example, the transformer only has to be de-rated 4% of its nameplate current rating.

In conclusion, there are three issues to review when connecting a power converter to a 480 VAC bus. The first issue is the bus voltage distortion. Line reactors and phase-shifting components can reduce this distortion. For severe cases, tuned filters can further improve this issue but are not addressed in this document.

The second issue is voltage notching. Depending on the type of system and the percentage it is loaded with power converter equipment, correcting for voltage distortion alone may not be enough.

The last issue is how much the feeder transformer has to be de-rated to supply the power converter loads. ANSI C57.110-1986 addresses this in detail.

Addressing these three issues will improve the power quality at the point of common coupling (the 480 VAC bus in this document) and minimize problems and interactions with other pieces of equipment.

Submitted by
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References:

1. IEEE Standard 519-1992: “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”
2. Paice, Derek A., “Power Electronic Converter Harmonics”, IEEE Press, 1995, Chapters 7 and 8
3. Lye, R. W., et. al., “”Power Converter Handbook”, Canadian General Electric Company Limited, 1976, Chapters 6 and 7.
4. ANSI standard C57.110-1986, “IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Currents”